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(54) MEASURING APPARATUS EMPLOYING AN ELECTRO-OPTIC TRANSDUCER

(71) We, CENTRAL ELECTRICITY GENERATING BOARD, a British Body Corporate, of Sudbury House, 15 Newgate Street, London, EC1A 7AU, do hereby declare the invention, for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:-

This invention relates to measuring apparatus employing an electro-optic transducer.

A number of proposals have been made in recent years for employing passive optical effects, such as magneto-optic and electo-optic effects in transducers. Such apparatus finds particular application in making measurements on high voltage transmission lines. As is described in the Paper "Method for Simultaneous Measurement of Current and Voltage on High Voltage Lines Using Optical Techniques" by Dr A.J. Rogers (Proc. I.E.E. Volume 123, No.10, Oct. 1976) voltage and current measurements may be made using, as a transducer, a material such as alpha quartz which exhibits both magneto-optic effects and electro-optic effects.

When linearly polarised light passes through a medium under the influence of a magnetic field, the direction of polarisation will, in general, be rotated. This phenomenon is known as the Faraday magneto-optic effect. The rotation which occurs is proportional to the line integral of the magnetic field along the propagation path. All materials exhibit the Faraday effect. The effect is weakest for diamagnetic materials and stronger, successively, for paramagnetics and ferromagnetics. Only for diamagnetics however is the effect independent of temperature and hence these diamagnetic materials are of more particular interest in measuring apparatus using magneto-optic effects.

The electro-optic effect is the name given to the dependence of the linear birefringence on the external electric field. Linear birefringence in a medium (usually a crystalline material) is that phenomemon whereby two orthogonal linear directions of polarisation of the light propagating in the medium travel at different velocities. The linear birefringence in a medium is characterised by an ellipsoid, known as the index ellipsoid, which defines the way in which the two velocities due to the birefringence vary with direction when referred to crystallographic axes. The electro-optic effect is a result of the distortion of the index ellipsoid caused by application of an electric field.

The electro-optic effect depends on the electric field and thus gives a possible way of measuring such a field. However, materials which produce a significant electro-optic effect usually also produce polarisation rotation due to the magneto-optic effect; in other words there is polarisation rotation due to the magnetic field. In measuring the electric field, it is necessary to discriminate between these two effects.

As described in the abovementioned Paper, if a quartz element is placed adjacent a high voltage transmission line and light is transmitted through that element, this light will be subjected to both magneto-optic and electro-optic effects and it is possible, by utilising two similar quartz elements, one on either side of the electric current-carrying element (so that the magneto-optic effects in the two elements are in opposite senses) to produce two signals which can be processed to obtain outputs dependent on the magnetic and electric fields and hence to obtain measures of the current through the line and of the local electric field which is dependent on the voltage on the line.

The arrangement described in the aforementioned publication however required the transmission of a light signal through two separate paths and the measurement of their

amplitudes. This introduces a serious source of error, particularly in equipment which is used out-of-doors. Local conditions in one of the paths may affect the amplitude of the signal in that path. More particularly however photo-transducers such as photo-diodes commonly have a non-uniform sensitivity to light over the surface area of the diode. Hence relative movement, fibration and the like cause errors in amplitude reading.

It is an object of the present invention to provide an improved form of measuring apparatus employing a transducer exhibiting magneto-optic and electro-optic effects on an incident polarised light source in which the electro-optic and magneto-optic effects are separated at the light beam receiver which receives the beam after it has passed through the transducer element. Thus, over the light path between the light transmitter and transducer and light receiver, only a single light path is employed.

According to the present invention in measuring apparatus having a transducer which, when subjected to electric and magnetic fields, produces magneto-optic rotation of the plane of polarisation of linearly polarised incident light and also produces electro-optic changes in the linear birefringence, giving rise to changes in relative phase delays of orthogonal linearly polarised components of light passing through the transducer, there is provided a light source producing polarised light incident on said transducer, a photo-detector for receiving light passing through said transducer and arranged to provide an output signal dependent on the intensity of the incident light on the photo detector and adjustable analysing means between the transducer and the photo-detector and arranged to transmit to said photo-detector only linearly polarised light in a selected plane of polarisation, said analyser having means for selectively passing to said photo-detector light polarised at 0° and at 45° to the fast axis of the transducer.

By measuring the light intensity at the photo-detector with the analyser set at these two different settings, the two output values enable the instantaneous values of the linear birefringence and the circular birefringence to be obtained and hence indications are obtained representative separately of the magnitudes of the magnetic field and of the electric field in which the transducer is located.

The processed output signals may be utilised in indicating means or in recorders or may be utilised for control purposes.

To explain the operation of this device, it is necessary firstly to consider the concepts of linear and circular birefringence.

In general it may be assumed that the transducer element will possess a non-zero residual (i.e. field-independent) value of each type of birefringence so that we may write for the linear birefringence, δ, and the circular birefringence, 2ρ, the expressions:-

$$\delta = \delta_o + \delta_e$$

$$2\rho = 2\rho_o + 2\rho_e$$

where δ_o and ρ_o are the non-zero residual values and δ_e and ρ_e are the changes in the birefringence due to the field at the transducer.

(The factor 2 in the circular birefringence derives from the fact that the phase retardation between the two oppositely rotating circularly polarized normal modes is twice the value of the rotation suffered by the linear polarization direction which they constitute).

The two normal modes which propagate under these conditions are elliptically polarized and suffer a relative phase delay Δ given by

$$\Delta = (\delta^2 + (2\rho)^2)^{\frac{1}{2}}$$

It can be shown that under these conditions an analyzing polarizer set at angle β with respect to the fast electro-optic axis will pass to a photo detector an intensity $I\beta$ given by:

$$\begin{aligned} I\beta = & [A_1^2 (a^2 + b^2) + A_2^2 c^2 - 2A_1A_2c\,(a \cos\psi - b \sin\psi)]\cos^2\beta \\ & + [A_1^2 c^2 + A_2^2 (a^2 + b^2) + 2A_1A_2c\,(a \cos\psi - b \sin\psi] \sin^2\beta \\ & + [ac\,(A_1^2 - A_2^2) - 2abA_1A_2 \sin_0 + A_1A_2 \cos\psi\,(a^2 - b^2 - c^2)] \sin 2\beta \end{aligned}$$

where the input amplitude components along the fast and slow axes, E_f and E_s respectively, are given by:

$$E_f = A_1 \exp [j\omega t]$$

$$E_s = \exp [j(\omega t + \psi)]$$

and where:

$$a = \cos \Delta/2$$

$$b = \delta/2 \sin \frac{\sin \Delta/2}{\Delta/2}$$

$$c = \rho \sin \frac{\sin \Delta/2}{\Delta/2}$$

By measuring the value of $I\beta$ at two values of β, enough information is obtained from the output polarization ellipse to yield the instantaneous values of δ and 2ρ, and hence,

independently, the values of electric and magnetic fields.

The analysis necessary to obtain values for δ and 2ρ from the intensity measurements can be performed either in analogue or digital electronics. With present technology, the limitations in speed of processing digitally would limit the measurement bandwidth to less than about 1 kHz. For many purposes however, e.g. for visual displays or for records, such a bandwidth limitation is not of importance.

In carrying the invention into practice, conveniently the light source comprises a laser with a linear polariser arranged to direct a linearly polarised light beam onto said transducer. The transducer may, for example, comprise one or more blocks of quartz arranged, as described later, to be electro-optically sensitive in the direction of propagation of the light beam. For measurements on transmission lines, busbars and the like, it is particularly convenient to use an optical fibre which is electro-optically sensitive in the axial direction; such a fibre can be arranged to extend from the light source, conveniently located on or near the ground, over the line or busbar and then back down to the light receiver which may be on the ground adjacent to the light source.

The transducer is responsive to the electric field. It is commonly required to measure a voltage; this voltage is the integral of the electric field along a path between the points of different potential. An optical fibre can be arranged to extend for example between a point at earth potential and the immediate neighbourhood of a high voltage conductor; if this fibre is electro-optic sensitive in the axial direction, it will in effect integrate the electric field between earth and the conductor irrespective of the local direction of the field in the immediate neighbourhood of any point along the length of the fibre. For some purposes however it is sufficient to measure the local field intensity and this may conveniently be done by a block of suitable material, e.g. a quartz block in the immediate neighbourhood of the conductor. In another arrangement, a series of such blocks are arranged along the light path. It will be appreciated that, in this case, the blocks, like the fibre, will integrate the components of field along the length of the various blocks. If these blocks do not extend along the whole path between for example earth and a high tension point, discrete blocks spaced along that path can give a close approximation to the total voltage difference along the length of the whole path.

The receiver may comprise a photo-diode constituting the photo-detector together with an adjustable polarisation analyser with means for alternately setting the analyser to pass light in the required two linear planes of polarisation onto the photo-diode.

The following is a description of one embodiment of the invention, reference being made to the accompanying drawing which illustrates diagrammatically apparatus for determining the current in and the voltage on a transmission line or busbar.

In the drawing a line 10 is located above on earth plane 11. In this diagram, there are shown two similar quartz blocks 12, 13 which extend from the earth plane to a region adjacent the line 10. In practice, for outdoor transmission lines or basbars, the distances would be such that a plurality of such blocks would have to be used. These blocks need not necessarily be in contact with one another; as previously explained, the apparatus will effectively integrate the fields along the length of the various blocks and, by disposing a number of blocks at discrete intervals in the field, an adequate measure of voltage may be obtained for many purposes. Alternatively an optical fibre which is electro-optically sensitive in the axial direction may be used as previously described. A laser 20 with a polariser 21 giving linearly polarised light is arranged to direct light onto one of the blocks 12. In this particular embodiment, the light emergent from the block 12 is reflected by a mirror 22 and passed through a 90° polarisation rotator 23 onto a second mirror 24 which reflects the light down through the block 13. The two blocks of quartz are arranged so that the electric field of the system bears the same relationship to the crystal axes in each of the blocks. The mirrors 22, 24 can turn the light propagation direction through 180°, the two mirrors forming a double 45° reflector arrangement. Any polarisation effect introduced by the first reflection is cancelled by the second with the aid of the 90° rotation plate 23 interposed between the two mirrors. In the second block 13, the crystal axes are so arranged that the electro-optic effect now bears the opposite relationship to the natural birefringence when compared with the first block and also the natural birefringence delay is reversed in sign. There is thus a total phase delay which is dependent only on the electro-optic effect and not at all on a natural birefringence, a feature which renders the delay very largely independent of temperature. The output light beam is passed through an analyser 25 onto a photo detector 26 which provides an output voltage fed to computing means 27. Means 28 are provided for automatically adjusting the setting of the analyser so that the photo-diode receives alternately light which is at 0° and at 45° with respect to the fast axis of the quartz block 13 where the light is leaving that block. The signal processing means, as previously explained, determines, from the two alternate magnitudes of instant light, independent

values of the linear birefringence and the circular birefringence and hence give outputs representative of the magnetic and electric fields.

WHAT WE CLAIM IS:-

1. Measuring apparatus having a transducer which, when subjected to electric and magnetic fields, produces magneto-optic rotation of the plane of polarisation of linearly polarised incident light and also produces electro-optic changes in the linear birefringence, giving rise to changes in relative phase delays between orthogonal linearly polarised components of light passing through the transducer, wherein there is provided a light source producing polarised light incident on said transducer, a photo-detector for receiving light passing through said transducer and arranged to provide an output signal dependent on the intensity of the incident light on the photo-detector and adjustable analysing means between the transducer and the photo-detector and arranged to transmit to said photo-detector only linearly polarised light in a selected plane of polarisation, said analyser having means for selectively passing to said photo-detector light polarised at 0° and at 45° to the fast axis of the transducer.

2. Apparatus as claimed in claim 1 wherein said analyser means comprises an adjustable polarisation analyser with means for alternately setting the analyser to pass light in the required two linear planes of polarisation to said photo-detector.

3. Apparatus as claimed in either claim 1 or claim 2 wherein the photo-detector comprises a photo-diode.

4. Apparatus as claimed in any of the preceding claims and having output signal processing means responsive to the magnitudes of the light intensity at the photo-detector with the analyser set at the two different settings to determine the instantaneous values of the linear birefringence and the circular birefringence and hence to determine separately the magnitudes of the magnetic field and of the electric field in which the transducer is located.

5. Apparatus as claimed in any of claims 1 to 4 wherein the light source comprises a laser with a linear polariser arranged to direct a linearly polarised light beam onto said transducer.

6. Apparatus as claimed in any of the preceding claims wherein the transducer comprises one or more blocks of quartz located in the electric and magnetic fields and arranged to be electro-optically sensitive in the direction of propagation of the light beam.

7. Apparatus as claimed in any of claims 1 to 6 and for measuring the voltage on a conductor wherein the transducer includes a block of material exhibiting magneto-optic and electro-optic effects on incident polarised light and arranged in the light path adjacent to the conductor.

8. Apparatus as claimed in claim 7 wherein the transducer includes further blocks of said material arranged in the light path for additively combining the effects of the electric field between a point substantially at earth potential and the neighbourhood of the conductor.

9. Apparatus as claimed in any of claims 1 to 5 wherein the transducer comprises an optical fibre which is electro-optically sensitive in the axial direction and which extends at least part of the way along the path between the light source and a receiver including said photo-detector.

10. Apparatus as claimed in claim 9 and for measuring a voltage on a conductor wherein the optical fibre extends from a point where the electric field is substantially at earth potential to a point adjacent to the conductor.

11. Apparatus as claimed in claim 9 and for measurements on a current-carrying conductor wherein the optical fibre extends from the light source over the conductor and back to said receiver adjacent the light source.

12. Apparatus as claimed in claim 11 wherein the light source and receiver are located where the electric field from the conductor is substantially at earth potential.

13. Apparatus for determining the current in and the voltage on a transmission line or busbar substantially as hereinbefore described with reference to the accompanying drawing.

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1570802 COMPLETE SPECIFICATION

1 SHEET *This drawing is a reproduction of the Original on a reduced scale*